

# Effect of Temperature on the Deformation Behavior of B2 Austenite in a Polycrystalline $\text{Ni}_{49.9}\text{Ti}_{50.1}$ (at.%) Shape Memory Alloy

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## Introduction

Superelasticity in austenitic B2-NiTi is of great technical interest and has been studied in the past by several researchers [1]. However, investigation of temperature dependent deformation in B2-NiTi is equally important since competing mechanisms of stress-induced martensite (SIM), retained martensite, plastic and deformation twinning can lead to unusual mechanical behaviors. Identification of the role of various mechanisms contributing to the overall deformation response of B2-NiTi is imperative to understanding and maturing SMA-enabled technologies. Thus, the objective of this work was to study the deformation of polycrystalline  $\text{Ni}_{49.9}\text{Ti}_{50.1}$  (at. %) above  $A_f$  (105 °C) in the B2 state at temperatures between 165–440 °C, and generate a B2 deformation map showing active deformation mechanisms in different temperature-stress regimes.

## Experimental Results

The material used in this study was a binary  $\text{Ni}_{49.9}\text{Ti}_{50.1}$  (at.%) alloy with stress-free transformation temperatures ( $M_s$ ,  $M_f$ ,  $A_s$  and  $A_f$ ) of 71, 55, 92, and  $105 \pm 2$  °C, respectively [2]. Several techniques were used for this study: *in-situ* and *ex-situ* mechanical testing, *in-situ* neutron diffraction, room-temperature and hot-stage transmission electron microscopy, and elasto-plastic self-consistent (EPSC) polycrystalline deformation modeling based on grain-level dislocation plasticity [3]. *In-situ* neutron diffraction experiments were carried out using SMARTS and HIPPO diffractometers at the Los Alamos Neutron Science Center. Four different samples, one each for 165, 230, 290 and 320 °C analyses, were used for *in-situ* testing. Each sample was isothermally loaded in uniaxial tension to 18% strain and diffraction data were acquired at a minimum of 10 different strain values. The level of SIM, determined from the neutron diffraction data, was found to vary with temperature, saturating at a martensite volume fraction ( $V_f$ ) of 0.25 at 165 °C and 230 °C, and 0.13 at 290 °C. No martensite was observed at 320 °C (Fig. 1a). After unloading, an average  $V_f$  of 0.12 was stabilized for samples tested at 165, 230, and 290 °C. Beyond the 0.5% elastic strain limit, hkl-specific lattice strains deviated from linearity and were very dependent on orientation (Fig. 1b) and temperature. In all cases,  $\{111\}_{B2}$  planes yielded first and accommodated the lowest strain, followed by  $\{110\}_{B2}$  planes that accommodated intermediate strain, and  $\{100\}_{B2}$  planes that accommodated the maximum strain. In addition, in the loading direction,  $\{110\}_{B2}$  texture gradually increased and  $\{111\}_{B2}$  texture gradually decreased with increasing

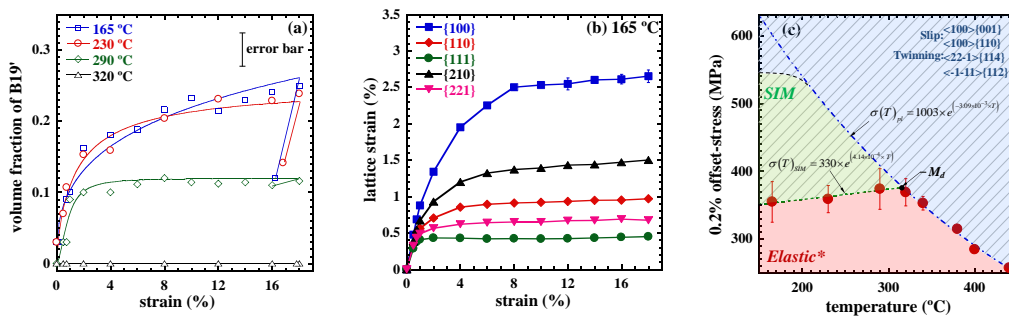


Figure 1: (a) Stress-induced martensite phase fractions during loading and unloading of  $\text{Ni}_{49.9}\text{Ti}_{50.1}$  at various temperatures, (b) Lattice strains associated with planes perpendicular to the loading axis at 165 °C, (c) Deformation-stress map showing the mechanisms responsible for the stress-strain behavior.

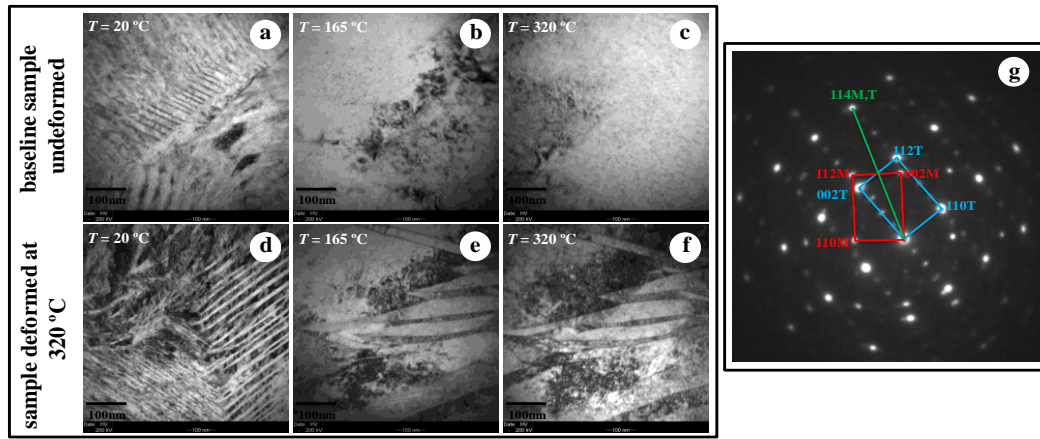


Figure 2: TEM bright-field (BF) images of the microstructure of  $\text{Ni}_{49.9}\text{Ti}_{50.1}$  at 20, 165 and 320 °C for the virgin sample (a, b, and c, respectively), and sample post-deformed to 18% strain at 320 °C (d, e, and f). (g) Selective area diffraction pattern (SADP) of the planar faults observed after deformation.

strain for all the samples. Both the lattice strains and texture effects were more pronounced at lower temperatures than at 320 °C.

Hot-stage TEM was conducted on the as-received sample and on 18% deformed samples tested at 165 °C and 320 °C. The results for only the as-received sample and the 320 °C-tested sample are shown in Fig. 2(a-f). The as-received sample showed self-accommodating martensite at room temperature and austenite at higher temperatures. The 165 °C-tested sample showed martensite at room temperature, and SIM, deformation twins, and a high density of dislocations at 165 °C and 320 °C. The 320 °C-tested sample, showed no SIM but only deformation twins and a high density of  $\langle 100 \rangle$  dislocations above  $A_f$ . The deformation twins were determined to be compound  $\{114\}_{B2}$  twins by SADP analysis (Fig. 2g).

Only the 320 °C sample was considered for the EPSC modeling since it had no SIM. Four cases with 3 different slip systems and 2 different twin systems were formulated in various combinations. It should be mentioned that no diffusion assisted deformation processes were considered in this model. The case that closely predicted the stress-strain response and experimental neutron diffraction results of texture and lattice strains was the one which contained both  $\langle 100 \rangle$  slip and  $\langle 22-1 \rangle \{114\}$  and  $\langle -1-11 \rangle \{112\}$  deformation twins.

Based on the experimental and modeling results, a B2-NiTi deformation map was constructed that highlights elastic, SIM and plastic regions in the 0.2% offset stress and temperature space (Fig. 1c). The boundary lines were formulated based on the experimental data using exponential functions, and the martensite desist temperature,  $M_d$ , was determined from this map as shown in Fig. 1c. More details can be found in Ref. [2].

## Conclusions

Isothermal deformation of B2- $\text{Ni}_{49.9}\text{Ti}_{50.1}$  (at. %) to 18% strain at temperatures between 165–440 °C consisted of recoverable strains from elastic and SIM and irrecoverable strains from retained SIM,  $\langle 100 \rangle_{B2}$  slip and  $\{114\}_{B2}$  deformation twins. A  $\{110\}_{B2}$  texture developed during deformation and lattice strain partitioning was observed with  $\{100\}_{B2}$  accommodating the maximum strain. The  $M_d$  temperature was determined to be between 310-320 °C. Above this temperature, no SIM was observed and the deformation was due to slip and deformation twins only. A deformation map outlining different deformation regimes was generated.

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